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Recovery of Forest Soil Chemical Properties Following Soil Rehabilitation Treatments: an Assessment Six Years after Machine Impact

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Abstract

Several rehabilitation treatments have been applied to mitigate runoff and sediment in machine trafficked areas following logging operations, while the knowledge on the consequence of these remediation techniques on the recovery of soil properties remains scarce. The objective of the study was to determine the effect of different rehabilitation treatments including sawdust mulch (SM), water diversion structure (WDS), untreated/bare trail (U), and undisturbed or control area (UND) on the recovery of soil chemical properties over a six-year period after machine-induced compaction occurred on three longitudinal trail gradients (10, 20, and 30%). In each treatment, the following soil properties were measured: litter thickness, pH, EC, soil organic C, total N, and available P, K, Ca, and Mg. Five sampling plots (with 10 m length and 4 m width) were positioned in each trail gradient classes and three of these plots were randomly considered for soil sampling. The results demonstrate that litter thickness differed among the three treatments, with the highest amount present on the UND area and lowest on the U treatment. Meanwhile, the highest pH (6.75), EC (0.21 Ds m^{-1}), N (0.27%), available P (14.61 mg kg^{-1}), available K (123.5 mg kg^{-1}), available Ca (135.1 mg kg^{-1}), and available Mg (42.1 mg kg^{-1}) and the lowest C (1.21%) and C/N ratio (7.83%) were found on the SM with gradient of 10% compared to other gradient classes on SM, WDS and, U treatments. The recovery value of litter depth, pH, EC, C, N, C/N ratio, and available nutrients (P, K, Ca, and Mg) were higher on the SM than the WDS at the gradient of 10%, while significantly higher levels of these variables were measured under WDS installed on trail gradients of 30% and 20% when compared with the same gradients on SM. Results of the study revealed that soil chemical properties showed some evidence of recovery following SM and WDS rehabilitation treatments compared to U, although these properties did not fully recover within 6 years as compared to UND area.

Keywords: soil compaction, soil health, soil protection, mulching, water diversion structure

1. Introduction

Mechanized forest harvesting systems, particularly machines used for wood extraction, have shown trends of heavier gross mass and payloads, resulting in a potential for increased soil compaction and disturbance (Labelle and Jaeger 2011, Jourgholami et al. 2014, Cambi et al. 2015, Jourgholami et al. 2019b). The in-stand traffic of these machines is often performed directly on soils, which results in increased bulk density (Merino et al. 1998, Cambi et al. 2017), decreased soil porosity (Bottinelli et al. 2014, Fründ and Averdiek 2016), reduced air permeability (Goutal et al. 2013), and reduced water infiltration rate (Croke et al. 2001, Toivio et al. 2017), thus contributing to forest soil degradation and tree growth impediments (Labelle and Kammermeier 2019). Machine-induced soil compaction also negatively influences the nutrient availability and soil fauna (Etehadi Abari et al. 2017). The degradation of soil physical properties following soil disturbance alters soil-water relations and hydrological processes under the soil upper layer, which leads to surface water flow as well as runoff and sediment deposition on downstream networks (Gökbulak et al. 2008, Jourgholami et al. 2017). However, soil compaction may not always alter microbial processes and can, in some instances, improve soil water holding capacity on sandy soils (Shestak and Busse 2005).

Ground-based harvesting operations not only decrease canopy percentage through the removal of target trees but also displace and reduce the intact litter layer (Stuart and Edwards 2006, Etehadi Abari et al. 2017), which plays a key role on the entry of water, energy, and nutrient into substrate layers, and protects the surface soil from raindrop impacts (Stuart and Edwards 2006, Sayer 2006). A significantly higher amount of runoff and sediment following forest harvesting has been reported by several researchers (Sawyers et al. 2012, Webb et al. 2012, Wear et al. 2013, Jourgholami et al. 2017). Some Best Management Practices (BMPs) including mulching, seeding, contour-felled log erosion barriers have been proposed, implemented, and tested to mitigate impacts to the soil from ground-based skidding located on trails trafficked by machines and landing areas where wood is stored (Stednick 2008, Wade et al. 2012, Webb et al. 2012, Jourgholami and Etehadi Abari 2017, Jourgholami et al. 2017).

Agricultural straw, wood strands, wood fibers, hydromulch, etc. are known as organic mulch that can provide ground cover once scattered on the soil surface. In turn, they can protect soil aggregates from the direct impact force of raindrop hitting the surface soil, control soil temperature and moisture, increase infiltration rate, and decrease runoff volume. Previous studies indicated that the application of organic mulch was effective to reduce post-harvest runoff and sediment (Wade et al. 2012, Wagenbrenner et al. 2015, Cristan et al. 2016, Jourgholami and Etehadi Abari 2017). However, the efficacy of applying mulch for erosion control depended on trail gradient, soil type, and mulch type (Smets et al. 2008). The presence of mulch covers dispersed on the soil surface influences soil properties and hydrological processes (Smets et al. 2008). Mulch can also affect soil fauna, which is necessary for the decomposition rate of organic matter, mineralization of nutrient, and improvement of soil quality (Merlim et al. 2005). Jourgholami and Etehadi Abari (2017) found that rice straw mulch reduced runoff and sediment by 50 to 60% after ground-based skidding operations performed on compacted machine operating trails as compared to uncovered soil. Furthermore, organic mulch can act as a supplementing source of organic matter, which in turn stimulates the decomposition rate on the topsoil.

Another method to suppress runoff and sediment is the use of water diversion structures or contour-felled log erosion barriers. These features consist of logs installed on the ground in a shallow trench oriented in a parallel or diagonal direction to contour lines, thus providing mechanical barriers to overwhelming flow, diminishing slope length, increasing infiltration, maintaining surface roughness, and trapping sediments (Yanosek et al. 2006, Robichaud et al. 2008, Prats et al. 2016). The efficiency of contour felled logs highly depends on the installation quality and storage capacity, while the effectiveness of water diversion structures dramatically declines during heavy storm events (Robichaud et al. 2008). For slope rehabilitation treatments, distance between consecutive structures is decreased with higher slope. By attenuating runoff flow, the contour-felled logs, in turn, can provoke the restoration processes of soil physical and chemical properties through the dispersion of the overland water to the intact forest floor (Prats et al. 2014).

Rehabilitation and stabilization treatments including mulching, seeding, and contour-felled erosion barriers can be applied to alleviate runoff and soil loss immediately after wildfire and forest harvesting (Jordán et al. 2010, Díaz-Raviña et al. 2012, McCullough and Endress 2012, Lombao et al. 2015). In fact, the effectiveness of these treatments on physiochemical and microbiological soil properties has been well documented following wildfire. However, the level of knowledge of the influence of rehabilitation treatments on recovery of soil quality after machine impact remains scarce, particularly when considering soil chemical properties. Jourgholami et al. (2018) concluded that the recovery values of soil bulk density, total porosity, penetration resistance and rut depth continued to show signs of machine-induced disturbance over a 6-year monitoring period.

Diverse responses of soil physical properties exposed to ground-based mechanized forest operations have been widely reported. The severity of the impact depends on initial soil density, harvesting system used, soil type, gradient of trail, climate, and time elapsed after compaction (Kozlowski 1999, Croke et al. 2001, Cambi et al. 2015). Soil recovery refers to the process of regaining or returning soil to a normal or natural state or restoration to a former or better condition. Physical properties of a severely compacted soil can take decades to naturally recover (Kozlowski 1999, Cambi et al. 2015). In the Flemish region, Belgium, Ampoorter et al. (2010) found that the compacted soil was not completely recovered within seven to nine years after mechanized harvesting. On the silty temperate-forest soils in northeastern France, Bottinelli et al. (2014) found that soil macroporosity recovered in the upper soil layer (7 cm) under natural condition over 2–3 years following heavy traffic. However, some studies indicated that recovery of compacted soil might persist 40–100 years (Greacen and Sands, 1980, Croke et al. 2001). Meyer et al. (2014) reported that planting black alders (*Alnus glutinosa* L. Gaertn.) initiated the recovery of compacted soil structure and porosity over seven years, however, the full recovery of soil parameters may take more time to return to uncompacted levels. Consequently, reclamation of soil physical and chemical properties without renewal and rehabilitation treatments is a prolonged process (Kleibl et al. 2014, Ebeling et al. 2016).

Unfortunately, the flood events occurring in the lowland and coastline areas located near the Caspian Sea have reached serious levels because of ground-based skidding operations in the upland region of the Hyrcanian forests. Mountainous area and climate condition (especially high rainstorm coinciding with leafless period of trees instantly after soil disturbance) have an inclination to increase runoff flow and sediment deposition to downstream networks. Therefore, mitigation and rehabilitation treatments should be engaged to reduce these impacts on forest soil and subsequently to metropolitan infrastructures and residents. This study aimed to assess the effects of mulching (SM) and water diversion structure (WDS) on the recovery of soil chemical properties of the topsoil of machine operating trails with varying gradients (10, 20, and 30%) exposed to heavy skidder traffic (10 machine passes), compared to untreated / bare trail (U), and undisturbed area (UND area) over six years after timber extractions under the mixed deciduous forest (north of Iran).

The SM and WDS treatments were applied directly on machine operating trails with two main intentions: first, to mitigate the surface runoff and soil loss after machine-induced soil compaction, and second, to rehabilitate the machine operating trail and return the quality of the soil to a condition similar to what is present in the tree-covered area. These intentions are pivotal since some trail segments may or may not be used upon re-entry, and it is therefore expected that trails be protected to allow them the opportunity to support unobstructed tree growth.

The hypothesis was that the rehabilitation treatments (SM and WDS) would create a protective layer over the soil surface and thus provide better conditions that would promote faster recovery of soil chemical properties as compared to uncovered trails U.

2. Material and Methods

2.1 Site and Machine Description

This study was conducted in the Kheyrud Forest Research Station located approximately seven kilometers east of Nowshahr in the Mazandaran province,

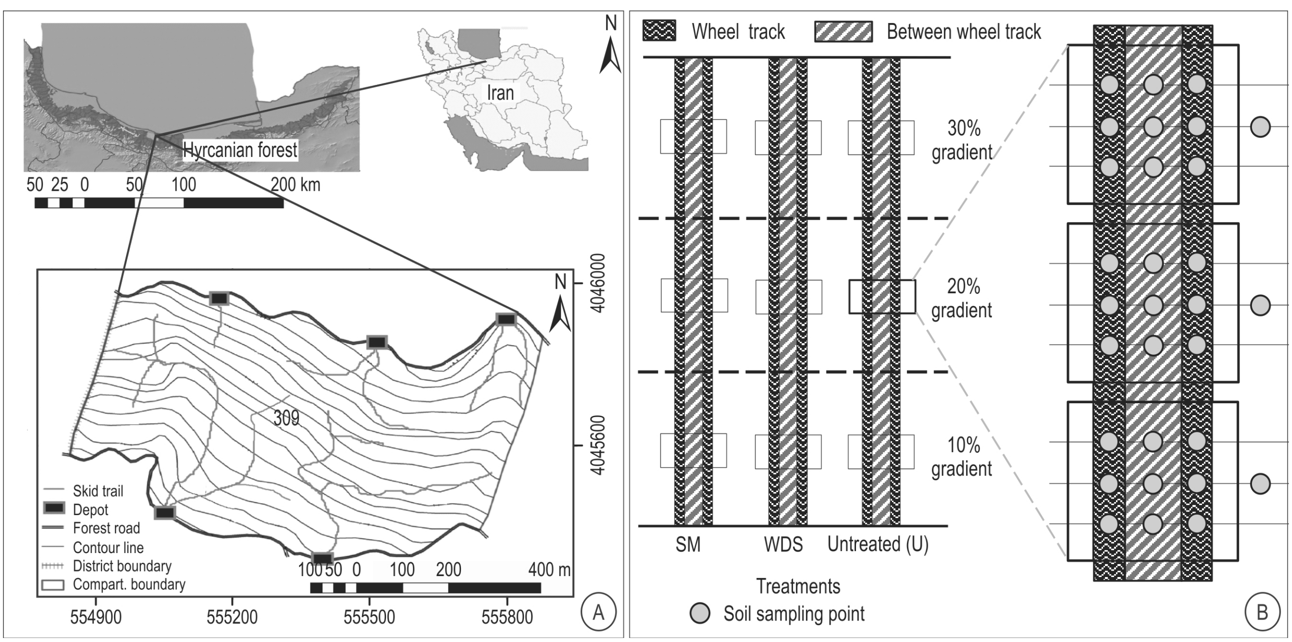

Fig. 1 Study area located in Gorazbon district in northern Iran (A), experimental design. SM, WDS, U, and UND are different treatments (B)

northern Iran. The research covers the compartment 309 in Gorazbon district (Fig. 1a). The study area is located from 990 to 1210 m above sea level on the south coast of the Caspian Sea with moderate topography comprised of slopes ranging from 0–30%. Deciduous broadleaved forests, with canopy cover ranging from 70–100%, are mostly composed of oriental beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* L.), oak (*Quercus castaneifolia* C.A.M.), alder (*Alnus subcordata* C.A.M.), and velvet maple (*Acer velutinum* Boiss.). The forest is managed by combined silvicultural treatments including group and single-tree selection harvests and has an average standing volume of 428 m^3 ha^{-1}. The mean annual precipitation is about 1260 mm yr^{-1}, with the largest share occurring during the summer and autumn seasons. The mean annual temperature is 8.6 °C and the highest and lowest temperatures are experienced in July and February, respectively. The dominated soil type is deep forest brown soil, which corresponds to both the upper Jurassic and lower Cretaceous periods. According to the unified soil classification system (USCS), the soil was identified and classified as CH or clay with a high plasticity. Soil bearing capacity (California Bearing Ratio), as determined with a dynamic cone penetrometer, was 10–12%. Classes were fine or thin and types of soil structure were blocky and subangular blocky structures.

A Timberjack 450C wheeled skidder was used to extract logs from the forest stand to a roadside landing. Specifics of the machine and corresponding loads were the following: an empty weight of 10.3 metric tons (load distribution of 55% and 45% between front and rear axles), 4 tires (24.5–32) without chains exerting average ground pressure of 220 kPa, average load volume of 3.4 cubic meters, numbers of logs per loaded pass ranged between 1 and 2, and log length ranged between 5–8 m, while the width of the machine operating trails was 3.5 m.

2.2 Experimental Design

Based on visual observations during the 2011 forest operations, segments of machine operating trails exposed to 10 machine cycles (a cycle consisted of one unloaded and one loaded pass) were selected for further investigation. Five sampling plots (with 10 m length and 4 m width) were positioned in each trail gradient class (10, 20 and 30%) and three of these plots were randomly selected for soil sampling. Instantly after machine traffic, the reclamation treatments of SM and WDS were applied to machine operating trails in each gradient class. The SM treatment was comprised of sawdust of beech and hornbeam species (1–5 cm in diameter and 0.4–14.0 cm in length) and it was applied on the surface of the compacted trail at a rate of 3.65 kg m^{-2}, which formed a 3 cm thick layer (Jourgholami et al. 2018). The WDS consisted of installing felled logs (25–30 cm in diameter and 4 m in length) perpendicular to the longitudinal axis of the machine operating trails. The spacing between consecutive felled logs was set at 10 m (Jourgholami et al. 2018). The untreated area (U) was also exposed to the same traffic intensity and the same three gradient classes as the other two treatments but did not receive any rehabilitation treatment. In July 2017 (6 years after harvesting), three sub-plots were established per plot for detailed soil sampling. Each sub-plot was composed of three transects (perpendicular to machine traffic), where soil samples were collected from the left and right wheel tracks and between tracks (three samples per transect). In addition, one soil sample per plot was collected at a distance of 20 m from the trails in the undisturbed forest area (UND area) to verify the undisturbed soil properties. Samples from the UND area were collected in each trail gradient class but will be reported as averages since their properties were very similar between gradients. In each treatment, the following soil properties were measured: litter thickness, pH, EC, soil organic C, total N, and available P, K, Ca, and Mg. In total, 270 soil samples were collected and analyzed (3 soil samples/transect × 3 transects/plot × 3 trail gradients × 3 treatments × 3 replicates + 1 soil sample/plot × 3 trail gradients × 3 treatments × 3 replicates) (Fig. 1b).

2.3 Soil Sampling and Analysis

At each measurement point, soil samples were taken at 0–10 cm from the surface soil with a steel cylinder (length of 40 mm and diameter of 56 mm). The thickness (depth) of litter was measured with a tape measure. The recovery levels of soil physical properties including soil bulk density (BD), total porosity (TP), penetration resistance (PR), and soil moisture (M) after SM and WDS treatments, compared to U trails and UND area, were also measured and analyzed. As this article focused on soil chemical properties, detailed information of sampling methodology for soil physical properties is explained in Jourgholami et al. (2018). Before gathering the soil samples, organic horizons were removed to provide access to the mineral soil. Soil samples were placed in bags, identified, transferred to the lab, air-dried, and sieved through a 2-mm sieve. An Orion Ionalyzer (Model 901) pH meter was used for measuring soil pH in a 1:2.5 ratio of soil:water (Salehi et al. 2013). The EC was recorded by an Orion Ionalyzer EC meter in a 1:2.5 ratio of soil:water (Salehi et al. 2013).

The Walkley-Black technique (Walkley and Black 1934) was used to measure soil organic C and the Kjeldahl method was applied for determining total N (Salehi et al. 2013). A spectrophotometer was used to determine the available phosphorous (P) by the Olsen method and an atomic absorption spectrophotometer was used to measure the available potassium (K), calcium (Ca), and magnesium (Mg) (Kooch et al. 2014).

2.4 Statistical Analyses

A factorial experiment with a complete block design was randomly assigned to the following factors: treatments (SM, WDS, U, and UND area), and trail gradients (10, 20, and 30%). Generalized linear modeling (two-way analysis of variance; ANOVA) was used to relate the recovery of soil chemical properties to treatment and trail gradient. The Kolmogorov-Smirnov test (α=0.05) was used to check the normality of soil properties. The Levene's test (α=0.01) was applied to verify the homogeneity of variance among treatments. The post hoc test was used to detect statistically significant differences between the treatment and trail gradient group means by the Duncan's multiple range tests with a 95% confidence level. To assess the relationship among soil physical and chemical properties, the Pearson correlation was applied. The analyses were performed using the SPSS software package (release 17.0; SPSS, Chicago, IL, USA). A principal component analysis (PCA) is a multivariate analysis method that investigates complex relationships among variables. Multivariate correlations were applied to evaluate significant relationships among principal components and variables by using the XLSTAT 2016 software.

3. Results

3.1 Soil Properties

Significant differences in soil chemical properties among the treatments were observed six years after mulch application. Soil properties including pH, available P, K, Ca and Mg were significantly influenced by trail gradient, but the litter thickness, EC, C, N, and C/N ratio were not significantly different among trail gradient classes. In addition, all tested soil chemical properties were influenced by the interaction between treatments and trail gradient with the exception of soil EC (Table 1).

The litter thickness under the SM located in 10% trail gradient was significantly higher compared to WDS and U treatments, while thicker litter amounts were found on the gradients of 20 and 30% under the WDS as compared to other treatments. The highest soil pH values were found on the SM of 10% gradient (6.75) followed by 30% and 20% gradients of the WDS treatment, whereas the lowest pH values were measured on the UND area. The largest amounts of organic

Table 1 Analysis of variance (ANOVA; *F* test and *p* value) for the effects of treatment and trail gradient and their interactions on soil chemical properties over a six-year period after traffic

Soil property	Treatment, 3 d.f.		Trail gradient, 2 d.f.		Treatment × Trail gradient, 6 d.f.	
	F test	*p* value	*F* test	*p* value	*F* test	*p* value
Litter thickness, cm	265.67	**<0.001**	1.14	0.320	12.89	**<0.001**
pH, 1:2.5 H_2O	323.26	**<0.001**	6.63	**0.002**	39.59	**<0.001**
EC, ds/m	51.41	**<0.001**	2.92	0.056	1.69	0.123
C, %	337.89	**<0.001**	0.61	0.545	3.49	**0.002**
N, %	129.55	**<0.001**	1.62	0.200	12.36	**<0.001**
C/N ratio	50.56	**<0.001**	0.05	0.954	5.99	**<0.001**
Available P, mg kg^{-1}	745.71	**<0.001**	36.31	**<0.001**	25.51	**<0.001**
Available K, mg kg^{-1}	1693.4	**<0.001**	45.98	**<0.001**	185.1	**<0.001**
Available Ca, mg kg^{-1}	1745.3	**<0.001**	115.5	**<0.001**	109.03	**<0.001**
Available Mg, mg kg^{-1}	535.03	**<0.001**	23.62	**<0.001**	42.93	**<0.001**

d.f. – degrees of freedom
Different treatments are included SM, WDS, U, and UND area
p values less than 0.05 are given in bold

Table 2 Means (±SE) of soil chemical properties by different treatment and trail gradient classes

Soil property	Treatment	UND	Trail gradient		
			10%	20%	30%
Litter thickness, cm	U	7.5±0.3 a	3.7±0.2 e	3.4±0.2 e	3.3±0.26 e
	SM	7.5±0.3 a	4.9±0.1 c	4.5±0.3 cd	4.5±0.2 cd
	WDS	7.5±0.4 a	4.4±0.2 d	5.7±0.2 b	5.7±0.2 b
pH, 1:2.5 H_2O	U	5.44±0.37 f	5.80±0.31 e	5.73±0.29 e	5.75±0.26 e
	SM	5.46±0.32 f	6.75±0.41 a	6.18±0.36 c	6.17±0.35 c
	WDS	5.43±0.29 f	6.06±0.35 d	6.33±0.37 b	6.36±0.42 b
EC, ds/m	U	0.31±0.08 a	0.17±0.04 c	0.16±0.03 c	0.16±0.06 c
	SM	0.29±0.09 a	0.21±0.06 b	0.17±0.05 c	0.17±0.04 c
	WDS	0.28±0.11 a	0.18±0.07 bc	0.19±0.04 bc	0.19±0.03 bc
C, %	U	5.32±0.28 a	2.36±0.15 b	2.59±0.17 b	2.71±0.26 b
	SM	5.36±0.35 a	1.21±0.19 e	1.64±0.22 cd	1.68±0.23 c
	WDS	5.32±0.32 a	1.63±0.11 cd	1.34±0.28 de	1.16±0.17 e
N, %	U	0.38±0.07 a	0.14±0.04 d	0.13±0.04 d	0.13±0.07 d
	SM	0.39±0.09 a	0.27±0.05 b	0.17±0.06 cd	0.16±0.06 cd
	WDS	0.38±0.08 a	0.14±0.03 d	0.20±0.07 c	0.19±0.04 c
C/N ratio	U	15.14±2.34 b	21.56±3.25 a	21.62±4.25 a	23.42±2.95 a
	SM	15.19±3.02 b	4.83±2.11 d	10.92±1.25 bc	12.25±1.74 bc
	WDS	14.25±2.52 b	14.92±2.34 b	7.27±1.56 cd	6.29±1.47 cd
Available P, mg kg^{-1}	U	20.45±3.46 a	6.41±1.33 f	5.61±1.05 g	5.46±0.95 g
	SM	19.30±2.92 a	14.61±3.41 b	8.93±1.45 e	8.32±1.39 e
	WDS	18.89±4.02 a	9.78±1.64 d	11.37±2.06 c	11.61±2.26 c
Available K, mg kg^{-1}	U	143.96±7.23 a	84.3±5.13 f	82.1±4.71 f	81.4±4.63 f
	SM	143.14±8.72 a	123.5±7.11 b	94.4±6.12 e	94.6±6.58 e
	WDS	138.73±9.02 a	99.2±4.74 d	113.6±6.14 c	112.2±6.27 c
Available Ca, mg kg^{-1}	U	167.22±9.1 a	87.6 ±7.8 e	74.9±6.9 f	70.8±6.9 f
	SM	162.49±11.2 a	135.1±8.6 b	101.9±7.4 d	96.5±8.5 e
	WDS	159.32±10.6 a	110.3±9.1 d	125.8±9.2 c	117.4±7.8 c
Available Mg, mg kg^{-1}	U	49.72±4.12 a	25.2±4.60 e	22.4±4.35 f	21.8±2.20 f
	SM	46.04±3.80 a	42.1±5.10 b	32.5±2.90 d	31.4±3.80 d
	WDS	45.40±4.20 a	31.7±2.91 d	36.8±3.70 c	37.7±4.10 c

Different letters in each soil property indicate significant differences among trail gradient classes and treatments (p<0.01) based on Duncan's test over a six-year period after traffic

C were detected on the UND area and ranged between 5.32 and 5.36%, whereas organic C was significantly lower on the U treatment compared with the UND area. Application of SM and WDS had a significant effect on organic C. At a gradient of 10%, the highest amount of organic C was detected on the WDS treat-

Table 3 Pearson correlations between soil physical properties and litter thickness and soil chemical properties

Soil properties	pH	EC	C	N	C/N	P	K	Ca	Mg
BD	0.37**	–0.39**	–0.51**	–0.41**	–0.01 ns	–0.41**	–0.41**	–0.34**	–0.30**
TP	–0.34**	0.39**	0.51**	0.41**	0.01 ns	0.41**	0.41**	0.34**	0.30**
PR	0.43**	–0.41**	–0.59**	–0.48**	–0.02 ns	–0.51**	–0.48**	–0.46**	–0.39**
M	0.04 ns	–0.04 ns	–0.00 ns	–0.03 ns	0.05 ns	–0.09 ns	–0.12 ns	–0.09 ns	–0.06 ns
Litter thickness	0.01 ns	0.53**	0.32**	0.65**	–0.34**	0.78**	0.80**	0.80**	0.73**

Note: *p<0.05; **p<0.01; ns: not significant

ment as compared to SM. However, organic C was statistically higher on the SM with 30% and 20% gradients as compared with the same gradients under the WDS (Table 2).

The highest total N was observed under three gradient classes in the UND area followed by the SM with 10% gradient. Total N showed a significant decrease as trail gradient increased from 10 to 20% in the SM, while significantly increasing in the WDS as the trail gradient increased from 10 to 20%. Regardless of the gradient class, largest values of C/N ratio were found in the untreated trails (U) and were even larger than the values of C/N ratio for the UND area. The lowest levels of C/N ratio were observed on the SM in the gradient of 10% and on the WDS with gradients of 20 and 30%. Significantly higher values of available P, K, Ca, and Mg were observed in all trail gradient classes under UND area followed by the SM at a gradient of 10% > WDS with gradients of 30% and 20%, while the lowest amounts of available P, K, Ca, and Mg were recorded at all gradient classes on the U treatment (Table 2).

The Pearson correlation analyses show that BD[1] and TP were positively and significantly correlated with pH and negatively correlated with EC, C, N, C/N, and available P, K, Ca, and Mg. Soil TP significantly increased with increasing EC, C, N, C/N, and available P, K, Ca, and Mg, as well as with decreasing soil pH. Soil moisture was not significantly correlated with any other soil chemical properties. Likewise, litter thickness significantly decreased with increasing soil C/N ratio, and also with decreasing other soil chemical properties (Table 3).

[1] Soil physical properties (BD – bulk density, TP – total porosity, PR – penetration resistance, M – soil moisture) referred to the physical responses data published by Jourgholami et al. (2018).

3.2 Soil Recovery Levels

The highest litter recovery was measured in the SM treatment, while on the steepest gradient, the largest litter recovery was found in the WDS treatment. On the 10% trail gradient, the higher recovery rate of pH was detected on the SM treatment, whereas on the 20 and 30% gradients, the higher recovery values of pH were detected on the WDS. The recovery value of EC was significantly higher (by 23%) under the SM with 10% gradient compared to the WDS, while EC showed greater recovery under the WDS with 20% and 30% gradients (Fig. 2).

The recovery of organic C on the SM at a gradient of 10% was significantly higher than the value under the WDS with the same gradient. The recovery rate of total N revealed that the SM had a significant effect on the 10% trail gradient, while the WDS was more effective on trails with gradients higher than 10%. The recovery value of the C/N ratio was enhanced by applying the SM at a trail gradient of 10%, while the WDS was mostly effective on gradients higher than 10%. In the trail gradient of 10%, the recovery values of available P, K, Ca, and Mg were greater on the SM than the values measured with the WDS. In contrast, levels of available P, K, Ca, and Mg were higher with the WDS than the values of the SM on trail gradients greater than 10% (Fig. 2).

Based on the results of a principal component analysis (PCA) using multivariate correlations, the first two principal components including axis 1 and axis 2 explained 73.0% and 24.7% of total variance, respectively, and both explained the largest fraction by 97.7% of total variance. The UND area was correlated with litter thickness and soil physical (BD, TP, PR, and M) and chemical properties (e.g., C, N, EC, available P, K, Ca, and Mg), while the other treatments (e.g. U, SM, and WDS) were located in the left

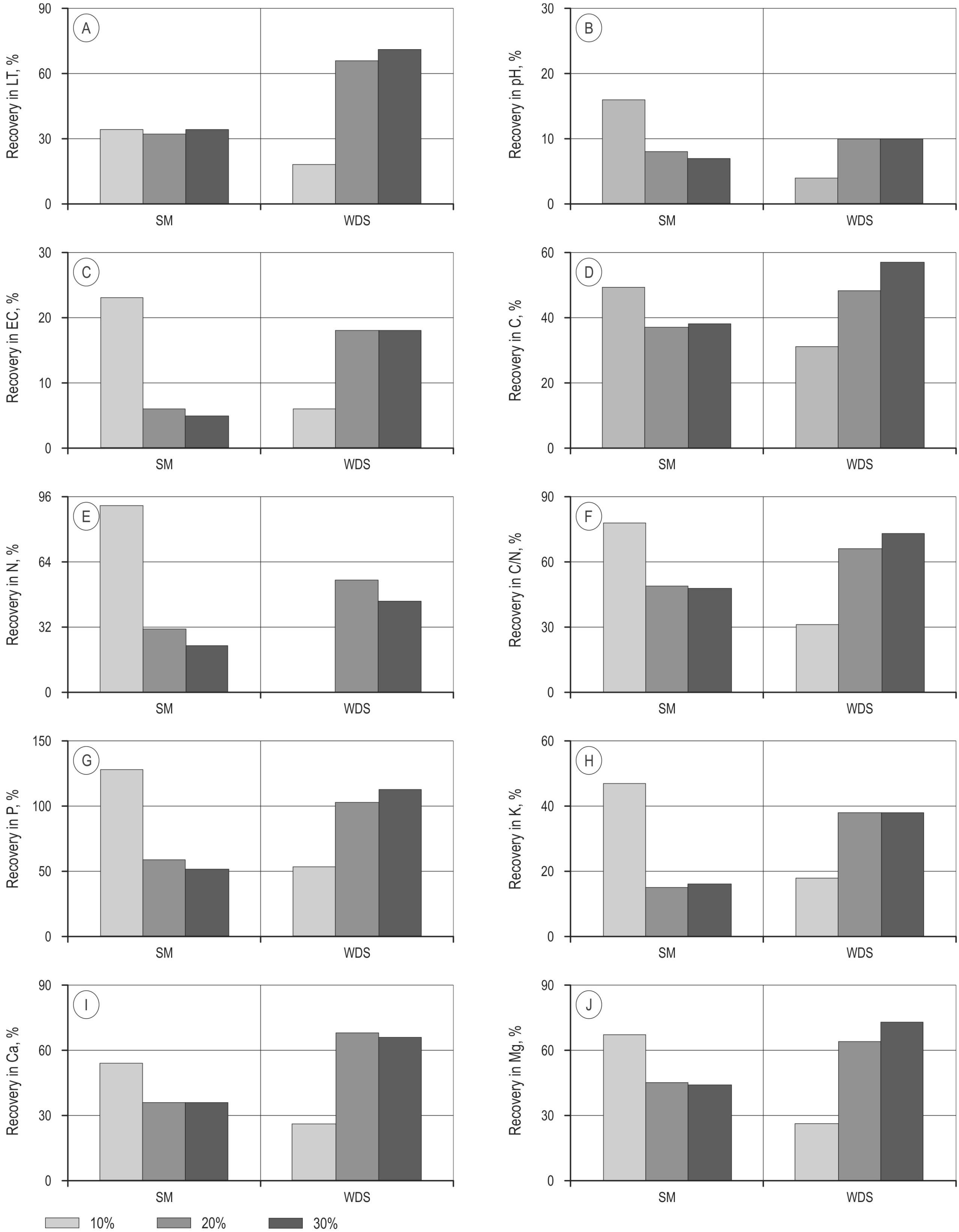

Fig. 2 Recovery value of litter thickness (A), pH (B), EC (C), C (D), N (E), C/N ratio (F), P (G), K (H), Ca (I), and Mg (J) by SM and WDS per trail gradient classes six years after skidding operations. Changes are relative to measurements from the same profile class in U treatment

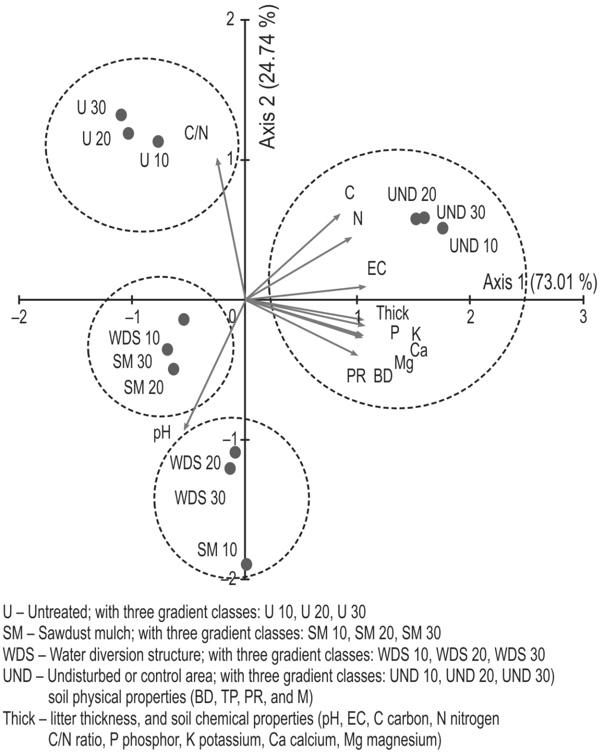

Fig. 3 Principal component analysis (PCA) ordination of the different treatments

PCA. The U treatment was positively correlated with soil C/N ratio, while both SM and WDS treatments were highly correlated with soil pH (Fig. 3).

4. Discussion

Results confirm that machine-induced soil disturbance and compaction lead to the reduction, and in some instances, complete removal of the litter layer that has a key role in maintaining soil quality as reported in previous studies (Sayer 2006, Stuart and Edwards 2006, Jodaugiene et al. 2010, Cambi et al. 2015, Jordán et al. 2010, Lombao et al. 2015). The removal of the litter layer can cause decreased food source, altered microclimate of surface soil, and decreased populations of soil fauna, which results in a decrease of soil porosity and aeration (Sayer 2006, Mulumba and Lal 2008, Frey et al. 2009, Majnounian and Jourgholami 2013). Six years after applying the reclamation treatments, the SM and WDS treatments showed that values of the tested soil chemical properties differed from the values of the corresponding UND area (acting as control). However, the recovery processes of soil chemical properties were slow to return and remained high on the untreated area (U). Several authors have concluded that recovery processes in soil chemical properties may take a few decades after machine-induced compaction (Greacen and Sands 1980, Croke et al. 2001, Bottinelli et al. 2014, Ebeling et al. 2016, Cambi et al. 2017). When considering soil physical properties, Jourgholami et al. (2018) demonstrated that soil bulk density and total porosity were partially recovered following SM and WDS rehabilitation treatments compared to U, although these properties did not fully recover 6 years after treatment, compared to UND area. Results of the current study are consistent with findings of Mulumba and Lal (2008) and Jordán et al. (2010), which support the application of organic mulch such as SM as a measure to reduce the bulk density and penetration resistance, enhance soil aggregate stability and water retention capabilities.

Six years after soil compaction and consequent treatments, litter depths and soil chemical properties were lower than those recorded in the corresponding UND areas in the three treatments (SM, WDS, and U). In the SM, litter thickness included the litter added due to litter fall every year and the amount of SM on surface soil. Results also revealed that the application of the SM (which was a mixture of beech and hornbeam species) created an appropriate cover on the soil surface that resulted in lowering the effects of raindrops, and could thus minimize soil particle detachment and transport on downstream networks. Accordingly, applying the SM has increased soil organic matter, decreased organic C, and decreased the C/N ratio in the surface layer of the soil.

The organic C and C/N ratio were significantly higher on the trail gradient of 10% with the SM than with the WDS, which was mainly due to the higher accumulation of organic matter and lower decomposition and mineralization rates. However, previous studies stated that some soil properties, such as accumulation of organic content, C/N ratio, and litter decomposition rate, were mostly related to tree species, soil type, and climate condition (Sayer 2006, Schaefer et al. 2009, Jodaugiene et al. 2010, Maggard et al. 2012). Moreover, mulch can also influence the temperature and moisture of the underlying soil by providing cover and thus shading the soil surface from direct solar radiation (Mulumba and Lal 2008, Jodaugiene et al. 2010, Jordán et al. 2010, Díaz-Raviña et al. 2012, Cristan et al. 2016). Hence, SM can play a key role in the soil rehabilitation process by favoring higher soil moisture retention and decreased soil temperature at the soil surface. These effects can stimulate biological activity and soil fauna, especially during dry summer seasons, where unprotected soils would be exposed to high soil surface temperature and water deficit (Jordán et al.

2010, Ampoorter et al. 2011, Cristan et al. 2016). Furthermore, soils in wetter climates recover faster from compaction than those in drier climates (Jordán et al. 2010, Fang et al. 2011). Similarly, Ampoorter et al. (2010) concluded that soil biological activities by soil fauna were effective in reducing high values of soil penetration resistance. Furthermore, fallen leaves from the canopy that are laying on the soil surface during the leafless period in the mixed-deciduous forest in the study area provided natural ground cover that reduced runoff and erosion risk. Considering that the study area has two dominant tree species, beech and hornbeam, it is preferable to use the logs and pulpwood in the construction of WDS from the beech species, which can persist against decay for a few years. Hornbeam logs decayed after two to three years and gradually rotted, while beech logs remained unrotten for several years and their decay rate was much slower than that of hornbeam logs, thus making beech a better option. Additionally, WDS can create mini-debris dams that can reduce water flow and increase infiltration and sediment deposition by allowing more time for the water to infiltrate the soil surface and percolate through the soil horizons (Foltz and Dooley 2003). However, when the sediment storage capacity for the area located above the log was reached, these features could no longer trap sediments effectively, especially during severe rain events in the late summer and early fall. In such instances, the efficacy of the WDS treatment was reduced drastically. Based on previous literature (Yanosek et al. 2006, Robichaud et al. 2008, Prats et al. 2016), the distance of 10 m between consecutive log erosion barriers is probably too short on a 10% trail gradient and the distances between log erosion barriers on the downslope should have differed for the 10, 20, and 30% treatments. As the terrain increased in gradient, distance between the log erosion barriers placed on machine operating trails should decrease.

Wagenbrenner et al. (2006) found that mulching was more effective than contour-felled logs to reduce runoff and sediment over three years after fire due to the ground cover increment after mulch application. Both SM and WDS can also affect soil water, particularly in the upper soil layer by diverting runoff flow, thus resulting in a reduction of water saturation in the pores in the surface soil layer that leads to further increase abiotic activity of pore space formation, and enhance air-soil gas exchange, diffusion and soil aeration. Following the SM decomposition processes from organic matter into other products, the soil organic C accumulation was decreased in the soil surface, which resulted in a significantly higher C/N ratio with the SM treatment on a trail gradient of 10%. Many authors have reported that mulch decomposition rate, density and cover percentage can affect the recovery of the post-harvest soil quality (Prats et al. 2012, Robichaud et al. 2013, Lombao et al. 2015, Fernández and Vega 2016, Jourgholami et al. 2019a).

5. Conclusions

The effects of different soil rehabilitation treatments, including sawdust mulch (SM), water diversion structure (WDS), and untreated / bare trail (U) from compacted soil, on the recovery of soil chemical properties located on machine operating trails with three longitudinal gradients (10, 20, and 30%) were examined over a six year period and compared to the values measured in UND area. Our hypothesis that both rehabilitation treatments would provide faster recovery of soil chemical properties as compared to uncovered plots (U) was supported by our data. However, tested soil properties were not fully recovered over the six-year period as compared to the UND areas.

Based on the results of the current study, the following management approaches can be addressed to rehabilitate machine operating trails after ground-based skidding operations:

- ⇒ SM is suitable for the reclamation practice and mitigating runoff and soil loss in machine operating trails with a gradient of 10% or less
- ⇒ WDS is a proper method to mitigate the adverse effects of soil compaction and decrease runoff and soil loss in the trail with a gradient higher than 10%
- ⇒ The longevity of SM should be considered before application and deterioration rate should be linked to how long the mulch is expected to provide protection to the soil
- ⇒ The longevity, durability, and proper installation have an important influence on the efficacy of WDS treatments. Beech logs are more durable than hornbeam logs
- ⇒ The optimal SM rate (kg m^{-2}) and appropriate distance between WDS require further investigations, particularly when considering varying terrain topography.

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